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THREE YEAR FINAL REPORT

FEMTOSECOND CARRIER PROCESSES IN COMPOUND
SEMICONDUCTORS AND REAL TIME
SIGNAL PROCESSING

MAY 1, 1990 - APRIL 30, 1993

CONTRACT #F49620-90-C-0039

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13. ABSTRACT (Maximum 200 words)

This report is the final report on research conducted under the auspices of the Joint Services Electronics Program at Cornell University. The research is grouped under two themes: (a) femtosecond carrier processes in compound semiconductors, and (b) real time signal processing. Results on OMVPE materials growth, femtosecond laser probing of hot carriers, and ensemble Monte Carlo simulations are reported on under the first theme. Accomplishments on VLSI algorithms, fault tolerance architectures, and architectures with multiple functional units for signal processing are given under the second theme.

TABLE OF CONTENTS

Directors Overview

This document is the final report of the Cornell Joint Services Electronics Program for the period from May 1, 1990 to April 30, 1993. This program carried two themes: femtosecond carrier processes in compound semiconductors, and real time signal processing. Seven task investigators, Profs. R. Shealy, C. Tang, C. Pollock, P. Krusius, G. Bilardi, A. Bojanczyk, F. Luk, and H. Torng, with their graduate students have contributed to JSEP research during this period. A substitute task for G. Bilardi's effort with Prof. Adam Bojanczyk was started in September 30, 1991. F. Luk was on a leave of absence from Cornell University during the academic year 1991/92. He resigned from Cornell during the fall of 1992 in order to take a position of the chairman of the computer science department at Rensselaer Polytechnic Institute, but continued to supervise his JSEP graduate students to the end of this program. 13 graduate students have been partially, or fully, supported by JSEP during this three year period. A total of 69 publications and 12 theses were prepared in this period and are now various stages of processing. One MS and 11 PhD degrees have been awarded to JSEP supported students during this three year period.

<u>Femtosecond Carrier Processes in Compound Semiconductors</u>

Two major events have dominated the activities under the compound semiconductor theme. First, the successful multi-university optoelectronics proposal submitted to DARPA under the leadership of Prof. C. Tang, one of the JSEP investigators, resulted in the establishment of the Optoelectronics Technology Center (OTC) in September 1990 with primary participant from Cornell University, University of California Santa Barbara, and University of California San Diego. The Cornell part of the OTC proposal leveraged past JSEP research. The OTC had its "kick-off" meeting in December 1990 in Santa Barbara. C. Tang served as the overall director of the OTC, while Profs. R. Shealy and H. Craighead, in addition to C. Tang, served on the executive committee. All solid state JSEP investigators, Profs. R. Shealy, C. Tang, C. Pollock, and P. Krusius, are involved in the OTC research program. This program terminates in July 1993. In the proposal, "The Optoelectronics Technology Center-Phase 2", submitted to ARPA in June 1993, the participating universities detail the continuation of this research. This time the overall principal investigator is Prof. L. Coldren from the University of California at Santa Barbara with Prof. R. Shealy serving as the co-principal investigator. Prof. C. Pollock is one of the task leaders. Second, the new off-campus organometallic vapor phase epitaxial (OMVPE) compound semiconductor materials growth facility has been completed under the leadership of R. Shealy. The facility has a total area 5,000 sq. ft, with 1,800 sq. ft of class 10,000 clean room, and houses 3 OMVPE reactors, the first of which became operational during the second year of this period. The two other reactors are being readied for operation. The facility design sets new standards

for handling highly toxic hydride source and process gases including full secondary containment. This facility is operated within the School of Electrical Engineering under a Dean's oversight committee. It serves the compound semiconductor materials growth needs for a variety of research programs including JSEP, DARPA OTC, ONR and SDIO/IST.

Using the first OMVPE reactor Prof. Shealy and his students have perfected the flow modulation epitaxial (FME) process for the synthesis of advanced III-V structures. The FME process has been optimized for GaInP and GaInAs alloys lattice matched to GaAs and InP respectively. A new selective epitaxial technology has also been developed. Selectivity is achieved via an evaporated graphite mask patterned with deep UV ablation. Prof. Tang in his research has successfully demonstrated the first broadly tunable femtosecond source. This femtosecond parametric oscillator is continuously tunable in the wavelength range from 900 nm to 4 μm. With additional intracavity doubling ultrashort pulses from the near UV to the near IR at power levels of hundreds of mW have been generated. Technology transfer from this work has lead to the first commercial broadly tunable femtosecond sources. Profs. Pollock and Krusius have explored near band gap femtosecond carrier relaxation in the InGaAs/InP system using tunable femtosecond dual pulse correlation spectroscopy and self-consistent Monte Carlo simulation respectively. Band gap renormalization and dynamic screening have been identified as the most dominant phenomena affecting the details of electron and hole relaxation under these conditions.

Real Time Signal Processing

The four investigators involved in the real time signal processing theme, Prof. G. Bilardi, F. Luk, H. Torng and later A. Bojanczyk, have performed their work in a synergistic mode. H. Torng organized three "Project 2000" meetings at Cornell, June 1990, 1991, and 1992 respectively, to discuss computer engineering advances with academic and industrial researchers. Typically about 25 industrial representatives attend this two day meeting. F. Luk organized an SPIE meeting on real time signal processing in July 1990. These JSEP faculty, together with other computer engineering and systems faculty of the School of Electrical Engineering moved into the new Engineering and Theory Center (E&TC) building with new accommodations for graduate students and faculty. F. Luk and A. Bojanczyk were awarded a Warp computer by DARPA. This GE built machine was installed at the E&TC building in September 1990.

Listing of Principal Investigators

Task #1   J.R. Shealy, Professor of Electrical Engineering
OMVPE Growth of III-V Alloys for New High Speed Electron Devices

Task #2   C.L. Tang, Professor of Electrical Engineering
Femtosecond Laser Studies of Ultrafast Processes in Compound Semiconductors

Task #3   C.R. Pollock, Professor of Electrical Engineering
Ultrafast Interactions of Carriers and Phonons in Narrow Bandgap Semiconductor Structures

Task #4   J.P. Krusius, Professor of Electrical Engineering
Femtosecond Dual Carrier Transport and Optical Interactions in Compound Semiconductor Heterostructures

Task #5   G. Bilardi, Professor of Computer Science
Parallel Structures for Real-Time Adaptive Signal Processing

Task #6   F. Luk, Professor of Electrical Engineering
Fault Tolerant Beamforming Algorithms

Task #7   H.C. Torng, Professor of Electrical Engineering
Interrupt and Branch Handling for Real-Time Signal Processing Systems

Task #5'   A. Bojanczyk, Professor of Electrical Engineering
Parallel Structures for Real-Time Adaptive Signal Processing (Substituted for task #5)

OMVPE GROWTH OF III-V ALLOYS FOR NEW
HIGH SPEED ELECTRON DEVICES

Task #1

Task Principal Investigator: James R. Shealy
(607) 255-4657

DEGREES AWARDED

1. Steve O'Brien
"Interdiffusion of III-V Semiconductor Quantum Well Heterostructure and its Application to Integrated Electro-Optical Devices"
Ph.D., Electrical Engineering, January 1991

2. James Singletery
"Promising Solutions to Indium Phosphides Low Schottky Barrier"
Ph.D., Electrical Engineering, May 1991

3. James T. Bradshaw
"Characterization by Raman Spectroscopy of Graded Index-Separate Confinement Heterostructure Lasers and Short Period Strained Layer Superlattices"
Ph.D., Applied Physics, August 1991

4. Bobby Pitts
"Flow Modulation Epitaxy Using a Multichamber Organometallic Vapor Phase Epitaxy System"
Ph.D., Electrical Engineering, May 1993

ISEP PUBLICATIONS

1. J. Bradshaw and J. R. Shealy, "Characterization of GaAs/AlGaAs Graded Index-Separate Confinement Heterostructure Lasers by Raman Scattering," *J. Appl. Phys.*, 68 (1), 358-360 (July 1, 1990).

2. S. O'Brien and J. R. Shealy, "Selective Interdiffusion of GaInAs/AlInAs Quantum Wells by SiO_2 Encapsulation and Rapid Thermal Annealing," *J. Appl. Phys.*, 68 (10), 5256-5261 (November 15, 1990).

3. S. O'Brien, J. R. Shealy, and G. W. Wicks, "Monolithic Integration of an (Al)GaAs Laser and an Intracavity Electroabsorption Modulator Using

Selective Partial Interdiffusion," *Appl. Phys. Lett.*, 58 (13), 1363-1365 (April 1, 1991).

4. S. O'Brien and J. R. Shealy, "Wavelength Tunable Lasers Using Selective Partial Intermixing," accepted as a regular paper for IEEE/OSA Topical Meeting, Monterey, CA (April 9-11, 1991).

5. S. O'Brien, J. R. Shealy, and G. W. Wicks, "Monolithic Integration of an (Al)GaAs Laser and an Intracavity Electroabsorption Modulator Using Selective Partial Intermixing," accepted for Poster Session, CLEO '91, Baltimore, MD (May 12-17, 1991).

6. S. O'Brien, J. R. Shealy, F. A. Chambers, and G. Devane, "Tunable (Al)GaAs Lasers Using Impurity-Free Partial Interdiffusion," *J. Appl. Phys.*, 71 (2), 1067-1069 (January 1992).

7. J. Bradshaw, X. J. Song, J. R. Shealy, J. G. Zhu, and H. Ostergaard, "Characterization by Raman Scattering, X-Ray Diffraction, and Transmission Electron Microscopy of $(AlAs)_m(inAs)_m$ Short Period Superlattices Grown by Migration Enhanced Epitaxy," *J. Appl. Phys.*, 72 (1), 308-310 (July 1992).

8. B.L. Pitts, D.T. Emerson, and J.R. Shealy, "Arsine Flow Requirement for the Flow Modulation Growth of High Purity GaAs Using Adduct-Grade Triethylgallium," *Appl. Phys. Lett.*, 61, 2054-56 (Oct. 1992).

9. J. Singletery and J. R. Shealy, "The Use of Ultraviolet Radiation at the Congruent Sublimation Temperature of Indium Phosphide to Produce Enhanced InP Schottky Barriers," *Journal of the Electrochemical Society*, 2961-2968 (October 1992).

10. B.L. Pitts, D.T. Emerson, and J.R. Shealy, "Gas Phase Reactions of Trimethylamine Alane in low pressure Organometallic Vapor Phase Epitaxy of AlGaAs," Accepted for publication, *Appl. Phys. Lett.* 62 (15), 1821-1823 (April 1993).

11. B.L. Pitts, M. Matragrano, D.T. Emerson, D. Ast, and J.R. Shealy, "Coherency Limits of Tetragonal III-V In-Containing Alloys and Superlattices on GaAs and InP Substrates," *Inst. Phys. Conf. Ser.* (1993).}

12. B.L. Pitts, D.T. Emerson, M.J. Matragrano, and J.R. Shealy, "Growth of High Purity GaAs in Low Pressure Organometallic Vapor Phase Epitaxy Using Minimal Arsine," submitted to *J. Crystal Growth*, (June 1993).

13. B.L. Pitts, D.T. Emerson, M.J. Matragrano, and J.R. Shealy, "The influence of the Al-precursors, Trimethylamine Alane and Trimethylaluminum,

in the Flow Modulation Epitaxy of AlGaAs," submitted to . *Crystal Growth* (June 1993).

14. K.L. Whittingham, B.L. Pitts, and J.R. Shealy, "Selective Organometallic Vapor Phase Epitaxy Using De_ᵤ UV Laser Ablation of Carbon Masks submitted to *Applied Physics Letters* (June 1993).

REPORTABLE INVENTION(S)

None.

FEMTOSECOND LASER STUDIES OF ULTRAFAST PROCESSES IN COMPOUND SEMICONDUCTORS

Task #2

Task Principal Investigator: C. L. Tang
(607)255-5120

DEGREES AWARDED

1. E. S. Wachman
"Ultrafast Spectroscopy with a Novel Broadly Tunable cw Femtosecond Source"
Ph.D., Applied Physics, 1991

2. W. H. Loh
"Polarization Self-Modulation in Semiconductor Lasers"
Ph.D., Electrical Engineering, August, 1991

3. Y. Ozeki
"Study of Two-mode Optical Bistable Semiconductor Laser Diodes with Intra-cavity Saturable Absorbers"
Ph.D., Electrical Engineering, August, 1991

4. Wayne Pelouch
"Multi-wavelength Ultrafast Source Development and Spectroscopy"
Ph.D., Applied Physics, January, 1993

JSEP PUBLICATIONS

1. W. H. Loh, A. T. Schremer, and C. L. Tang, "Hysteresis and Multistable Behaviour in a Polarization Self-Modulated External Ring Cavity Semiconductor Laser," *Elect. Lett.,* 26 (20), 1666-1667 (September 1990).

2. W. J. Grande, J. E. Johnson, and C. L. Tang, "Characterization of Etch Rate and Anisotropy in the Temperature-Controlled Chemically Assisted Ion Beam Etching of GaAs," *J. Vac. Sci. Technol. B,* 8 (5), 1075-1-79 (September/October 1990).

3. W. J. Grande, J. E. Johnson, and C. L. Tang, "GaAs/AlGaAs Photonic Integrated Circuits Fabricated using Chemically Assisted Ion Beam Etching," *Appl. Phys. Lett.,* 57 (24), 2537-2539 (10 December, 1990).

4. C. L. Tang, W. Pelouch, and P. Powers, "Broadly Tunable cw Femtosecond Optical Parametric Oscillators," invited talk, CLEO '91, Baltimore, MD (May 1991).

5. C. L. Tang, Y. Ozeki, and J. Johnson, "Polarization Bistability in Semiconductor Lasers," CLEO '91, Baltimore, MD (May 1991).

6. C. L. Tang, "Femtosecond Optics," International Workshop on Lasers in Chemistry and Physics, Dalian, China, sponsored by UNESCO and the Chinese Academy of Sciences (May 22-28, 1991).

7. W. S. Pelouch, R. J. Ellingson, P. E. Powers, C. L. Tang, D. M. Szmyd, and A. J. Nozik, "Investigation of Hot Carrier Relaxation in Quantum Well and Bulk GaAs at High Carrier Densities," *Proceedings of 7th International Conference on Hot-Carriers in Semiconductors*, Nara, Japan (July 1991).

8. E. W. Wachman, W. S. Pelouch, and C. L. Tang, "CW Femtosecond Pulses Tunable in the Near- and Mid-infrared," *J. App. Phys.*, 70, 1893 (1 August, 1991).

9. Y. Ozeki, J. E. Johnson, and C. L. Tang, "Polarization Bistability in Semiconductor Lasers with Intracavity Multiple Quantum Well Saturable Absorbers", *Appl. Phys. Lett.*, 58, 1958 (1991).

10. Y. Ozeki and C. L. Tang, "Polarization Switching and Bistability in an External Cavity Laser with a Polarization-sensitive Saturable Absorber," *Appl. Phys. Lett.*, 58, 2214 (1991).

11. W. S. Pelouch, R. J. Ellingson, P. E. Powers, C. L. Tang, D. M. Szmyd, and A. J. Nozik, "Comparison of Hot-carrier Relaxation in Quantum Wells and Bulk GaAs at High Carriers Densities," *Phys. Rev.* B 45, 1450 (15 January, 1992).

12. W. S. Pelouch, R. J. Ellingson, P. E. Powers, C. L. Tang, D. H. Levi, and A. J. Novzik, "Hot Carrier Relaxation in Quantum Well and Bulk GaAs at High Carrier Densities: Femtoseconds to Nanoseconds," *Ultrafast Laser Probe Phenomena in Semiconductors and Superconductors*, 24-25 March, 1992, Somerset, NJ; SPIE Proceedings Series, 1677, 260-271.

13. C. L. Tang, W. R. Bosenberg, T. Ukachi, R. J. Lane, and L. K. Cheng, "Optical Parametric Oscillators," *Proceedings IEEE*, 80, 365-374 (1992).

14. R. J. Ellingson and C. L. Tang, "High-repetition Rate Femtosecond Pulse Generation in the Blue," *Optics Letters*, 17, 343-346 (March 1, 1992).

15. W. S. Pelouch, P. E. Powers, and C. L. Tang, "Ti:sapphire -Pumped, High-repetition-rate Femtosecond Optical Parametric Oscillator," *Optics Letters* 17 (15), 1070-1072 (August 1, 1992).

16. W. Pelouch, P. E. Powers, and C. L. Tang, "Self-starting Mode-locked Ring-cavity Ti:sapphire Laser," *Optics Letters*, 1581-1583 (November 15, 1992).

17. R. J. Ellingson and C. L. Tang, "High Power, High-repetition-rate Femtosecond Pulses Tunable in the Visible," *Optics Letters*, 18, 438-440 (March 15, 1993).

REPORTABLE INVENTION(S)

1. C. L. Tang, W. S. Pelouch, P. E. Powers, "Self-starting Mode-locked Ring Cavity TI:sapphire Laser," U.S. Patent to be filed.

2. C. L. Tang, P. E. Powers, and S. Ramakrishna, "OPO Using KTA Non-linear Crystals," U.S. Patent Application No. 08/058,110.

3. R. J. Ellingson and C. L. Tang, "Intracavity-doubled Tunable OPO," U.S. Patent Application No. 08/025,377.

4. W. S. Pelouch, P. E. Powers, C. L. Tang, "TI:sapphire-pumped, High Repetition Rate Femtosecond OPO," U.S. Patent Application No. 07/880,656.

5. D. Edelstein, E. Wachman, C. Tang, "Broadly Tunable High Repetition Rate Femtosecond OPO," U.S. Patent No. 5,017,806, issued 5/21/91.

6. C. Tang, W. Loh, Y. Ozeki, and A. Schremer, "Ultrahigh Frequency Optical Self-Modulation," U.S. Patent No. 5,172,382, issued 12/15/92.

7. W. Bosenberg, C. Lap, and C. L. Tang, "Pump Steering Mirror Cavity," U.S. Patent No. 5,033,057, issued 7/16/91.

8. W. Bosenberg, "Optical Walkoff Compensation in Critically Phase-matched Three-wave Frequency Conversion Systems," U.S. Patent No. 5,047,668, issued 9/10/91.

9. L. Cheng, C. L. Tang, and W. Bosenberg, "Tunable OPO," U.S. Patent No. 5,053,641, issued 10/1/91.

10. D. Edelstein, E. Wachman, L. Cheng, and C. Tang, "Femtosecond Ultraviolet Laser using Ultra-thin Beta Barium Borate," U.S. Patent No. 5,034,951, issued 7/23/91.

ULTRAFAST INTERACTION OF CARRIERS AND PHONONS IN NARROW BANDGAP SEMICONDUCTOR STRUCTURES

Task #3

Task Principal Investigator: C. R. Pollock
                                    (607) 255-5032

DEGREES AWARDED

1. Timothy Carrig
   "Characterization of New Color Center and Transition Metal Ion Lasers"
   Ph.D., Applied and Engineering Physics, August 1992

ISEP PUBLICATIONS

1. C. R. Pollock, B. J. Zook, D. Cohen, and A. Sennaroglu, "Direct Measurement of Ultrafast Carrier Processes in Optical Probing of GaInAs-Type Narrow Bandgap Semiconductors," SPIE Vol. 1282 Ultrafast Laser Probe Phenomena in Bulk and Microstructure Semiconductors III (1990).

2. B. J. Zook, C. P. Yakymyshyn, and C. R. Pollock, "Numerical Optimization of the Additive-Pulse Modelocked Laser," submitted to JOSA B, July, 1990.

3. D. Cohen and C. R. Pollock, "Femtosecond Electron Relaxation in InGaAs Lattice-Matched to InP," presented at SPIE conference 1677, Somerset, NJ (March 25, 1992).

4. A. Sennaroglu, T. J. Carrig, and C. R. Pollock, "Femtosecond Pulse Generation by Using an Additive-pulse Mode-locked Chromium-doped Forsterite Laser Operated at 77 K," *Optics Letters*, 17, 1216-18 (1992).

5. J. E. Bair, D. Cohen, J. P. Krusius, and C. R. Pollock, "Band Renormalization and Dynamic Screening in Near Bad Gap Femtosecond Optical Probing of InGaAs," manuscript submitted for publication to *Physical Review Letters* (April 1992).

6. A. Sennaroglu and C. R. Pollock, "Generation of 48 fsec Pulses and Measurement of Crystal Dispersion by using a Regeneratively-initiated Self-mode-locked Chromium-doped Forsterite Laser," accepted for publication in *Optics Letters*.

7. A. Sennaroglu, C. R. Pollock, and H. Nathel, "Generation of Tunable Femtosecond Pulses in the 1.21-1.27 µm and 605-635 nm Wavelength

Region by Using a Regeneratively Initiated Self-mode-locked Cr:forsterite Laser," submitted for publication to *IEEE Journal on Quantum Electronics* (March 1993).

8. D. Cohen and C. Pollock, "Experimental Studies of Fast Carrier Relaxation Near the Bandedge of InGaAs," paper in preparation.

REPORTABLE INVENTION(S)

None.

FEMTOSECOND DUAL CARRIER TRANSPORT AND OPTICAL INTERACTIONS IN COMPOUND SEMICONDUCTOR HETEROSTRUCTURES

Task #4

Task Principal Investigator: J. P. Krusius
(607) 255-3401

DEGREES AWARDED

1. Steven Richard Weinzierl
   "Two-Dimensional Monte Carlo Simulations of Submicron Unipolar and Bipolar Compound Semiconductor Devices with Ballistic Injection Cathodes"
   Ph.D., Electrical Engineering, January 1992

JSEP PUBLICATIONS

1. J. E. Bair, and J. P Krusius, "Simulation of Ultrafast Carrier Relaxation Processes in Pulse/Probe and Dual Pulse Correlation Probing of InGaAs Type Narrow Band Gap Semiconductors," Ultrafast Laser Probe Phenomena in Bulk and Microstructure Semiconductors III, Robert R. Alfano, Editor, *Proc. SPIE 1282*, 162-169 (1990).

2. S.R. Weinzierl and J. P. Krusius, "Ballistic Injection Cathodes in High Speed Three Terminal Devices: Do They Really Make a Difference," *Proceedings of the Thirteenth Biennial Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits*, pp. 357-365, IEEE, 1991.

3. S.R. Weinzierl and J. P. Krusius, "Heterojunction Vertical FET's Revisited: Potential for 225 GHz Large Current Operation, *IEEE Transactions on Electron Devices*, 39, (5), 1050-1055 (1992).

4. S.R. Weinzierl and J. P. Krusius, "Space Charge Effects on Ballistic Injection Across Heterojunctions," *IEEE Transactions on Electron Devices*, 39, (7), 1780-1782 (1992).

5. J. E. Bair and J. P. Krusius, "Investigation Of The Role Of Free Carrier Screening During The Relaxation Of Carriers Excited By Femtosecond Optical Pulses," Ultrafast Laser Probe Phenomena in Semiconductors and Superconductors, R.R. Alfano (Editor), *Proceedings of the SPIE*, Vol. 1677, 157 (1992).

6. J. E. Bair, D. Cohen, J. P. Krusius, and C. R. Pollock, "Band Renormalization and Dynamic Screening in Near Bad Gap Femtosecond Optical Probing of InGaAs," manuscript submitted for publication to *Physical Review Letters*, March 1993.

7. J. E. Bair and J. P. Krusius, "Monte Carlo Simulation of Near Band Gap Femtosecond Optical Experiments in Compound Semiconductors," manuscript in preparation, to be submitted for publication in Summer 1993.

REPORTABLE INVENTION(S)

None.

NOVEL VLSI ALGORITHMS AND ARCHITECTURES
FOR HIGH DATA RATE DIGITAL FILTERING

Task #5 (Terminated 1991)

Task Principal Investigator: Gianfranco Bilardi

DEGREES AWARDED

None.

JSEP PUBLICATIONS

1. K. Herley, "Space-efficient Representations of Shared Data," *Proceedings of the 2nd Annual ACM Symposium on Parallel Algorithms and Architectures*, 407-416, Crete, Greece (July 2-6, 1990).

2. P. Bay and G. Bilardi, "Deterministic On-line Routing on Area-universal Networks," *Proceedings of the 31st Annual Symposium on Foundations of Computer Science*, 297-306, St. Louis, Missouri (October 22-24, 1990).

3. G. Bilardi and F.P. Preparata, "Memory Requirements of First-order Digital Filters," Department of Computer Science, Cornell University, Technical Report (1991).

REPORTABLE INVENTION(S)

None.

PARALLEL STRUCTURES FOR REAL-TIME ADAPTIVE SIGNAL PROCESSING

Substitute Task #5

Task Principal Investigator: **Adam W. Bojanczyk**
                                  (607) 255-4296

DEGREES AWARDED

None.

ISEP PUBLICATIONS

1. A.W. Bojanczyk, J. Nagy and R. Plemmons, "Row Householder Transformations for rank-k Inverse Modifications," *Linear Algebra and its Applications*, to appear.

2. A.W. Bojanczyk, J. Lebak and S. Olszanskyj, "Rank-k Modification Methods for Recursive Least Squares Problems," Technical Report, School of Electrical Engineering, Cornell University (January 1993).

3. A.W. Bojanczyk and P. Van Dooren, "On Propagating Orthogonal Transformations in a Product of 2×2 Triangular Matrices," *Proceedings of the Kent Conference on Scientific Computing*, Kent State University, Kent, Ohio (April 1992).

4. A.W. Bojanczyk and P. Van Dooren, "Reordering Diagonal Blocks in Real Schur Form," *Proceedings of the NATO ASI Workshop on Real-time and Large Scale Computing*, Leuven, Belgium (August 1-15, 1992).

5. A.W. Bojanczyk, G.H. Golub and P. Van Dooren, "The Periodic Schur Decomposition. Algorithms and Applications," *Proceedings of the SPIE's Annual Meeting*, San Diego (July 19-24, 1992).

REPORTABLE INVENTION(S)

None.

FAULT TOLERANT BEAMFORMING ALGORITHMS

Task #6

Task Principal Investigator: F. T. Luk
(607) 255-5075

DEGREES AWARDED

None.

ISEP PUBLICATIONS

1. F. T. Luk, Editor, *Proceedings of SPIE Vol. 1348, Advanced Signal Processing Algorithms, Architectures and Implementations, SPIE - The International Society for Optical Engineering*, Bellingham, Washington, 53 papers/557 pages (1990).

2. A.W. Bojanczyk, L.M. Ewerbring, F.T. Luk, and P. Van Dooren, "An Algorithm for the Singular Value Decomposition of a Matrix Product," *Proceedings of SPIE Vol. 1348, Advanced Signal Processing Algorithms, Architectures and Implementations*, 382-393 (1990).

3. R.P. Brent, F.T. Luk, and C.J. Anfinson, "Checksum Schemes for Fault Tolerant Systolic Computing," in Mathematics in Signal Processing II, J. G. McWhirter, Ed., Clarendon Press, Oxford, 791-804 (1990).

4. A.W. Bojanczyk, L.M. Ewerbring, F.T. Luk, and P. Van Dooren, "An Accurate Product SVD Algorithm," *Proceedings of 2nd International Workshop on SVD and Signal Processing*, Kingston, Rhode Island, 217-228 (1990).

5. D. L. Boley and F. T. Luk, "A Well Conditioned Checksum Scheme for Algorithmic Fault Tolerance," Integration, *the VLSI Journal*, 12, 21-32 (1991).

6. J. Chun and F. T. Luk, "Algorithmic Sensor Failure Detection on Passive Antenna Arrays," *Proceedings of SPIE Vol. 1566, Advanced Signal Processing Algorithms, Architectures and Implementations II, SPIE - The International Society for Optical Engineering*, Bellingham, Washington, 483-492 (1991).

7. F. T. Luk, Editor, *Proceedings of SPIE Vol. 1566, Advanced Signal Processing Algorithms, Architectures and Implementations II, SPIE - The*

International Society for Optical Engineering, Bellingham, Washington, 46 papers/494 pages (1991).

8. F. T. Luk, Editor, *Proceedings of the SPIE Vol. 1770 Advanced Signal Processing Algorithms, Architectures, and Implementations III* - The International Society for Optical Engineering, San Diego, CA, 468 pages (July 19-21, 1992).

9. G. E. Adams, A. W. Bojanczyk, and F. T. Luk, "Computing the PSVD of Two 2 x 2 Triangular Matrices," *Proceedings of the SPIE Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations III*, <u>1770</u>, 43-59 (1992).

10. F. T. Luk and S. Qiao, "Analysis of a Linearly Constrained Least Squares Algorithm for Adaptive Beamforming," *Proceedings of the SPIE Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations III*, <u>1770</u>, 210-218 (1992).

11. T. J. Lee, F. T. Luk, and D. L. Boley, "Computing the Singular Value Decomposition on a Fat-Tree Architecture," Department of Computer Science, Rensselaer Polytechnic Institute, Technical Report No. 92-33 (November 1992).

REPORTABLE INVENTION(S)

None.

INTERRUPT AND BRANCH HANDLING FOR REAL-TIME SIGNAL PROCESSING SYSTEMS

Task #7

Task Principal Investigator: H. C. Torng
(607) 255-5191

DEGREES AWARDED

1. Harry Dwyer
   "A Multiple, Out-of-Order, Instruction Issuing System for Superscalar Processors"
   Ph.D., Electrical Engineering, September 1991

2. Deborah T. Marr
   "A Block-Based Dispatch Window for Multiple Out-of-Order Instruction Issue"
   M.S., Electrical Engineering, June 1992

JSEP PUBLICATIONS

1. H. C. Torng and Martin Day, "Interrupt Handling for Out-of-Order Execution Processors," Technical Report EE-CEG-90-5, Cornell University School of Electrical Engineering, Ithaca, NY (November 1990).

2. G. E. Daddis Jr. and H. C. Torng, "The Concurrent Execution of Multiple Instruction Streams on Superscalar Processors," *Proceeding of the 1991 International Conference on Parallel Processing*, I-76 to I-83 (August 1991).

3. H. C. Torng and Martin Day, "Interrupt Handling for Out-of-Order Execution Processors," *IEEE Trans. on Computers*, 42, 122-126 (January 1, 1993).

4. H. Dwyer and H. C. Torng, "An Out-of-Order Superscalar Processor with Speculative Execution and Fast, Precise Interrupts," *Proceedings of 25th Symposium on Microarchitectures*, 272- 281 (December 1992).

5. H. C. Torng, H. Dwyer, and D. Marr, "On Instruction Windowing for Fine Grain Parallelism in High-Performance Processors," invited paper and in *Proceedings of 1993 International Phoenix Conf. on Comp. and Communications*, 98-104 (March 23-26, 1993).

REPORTABLE INVENTION(S)

None.

JSEP
HIGHLIGHT TRANSPARENCIES
FOR THE FOLLOWING TASKS:
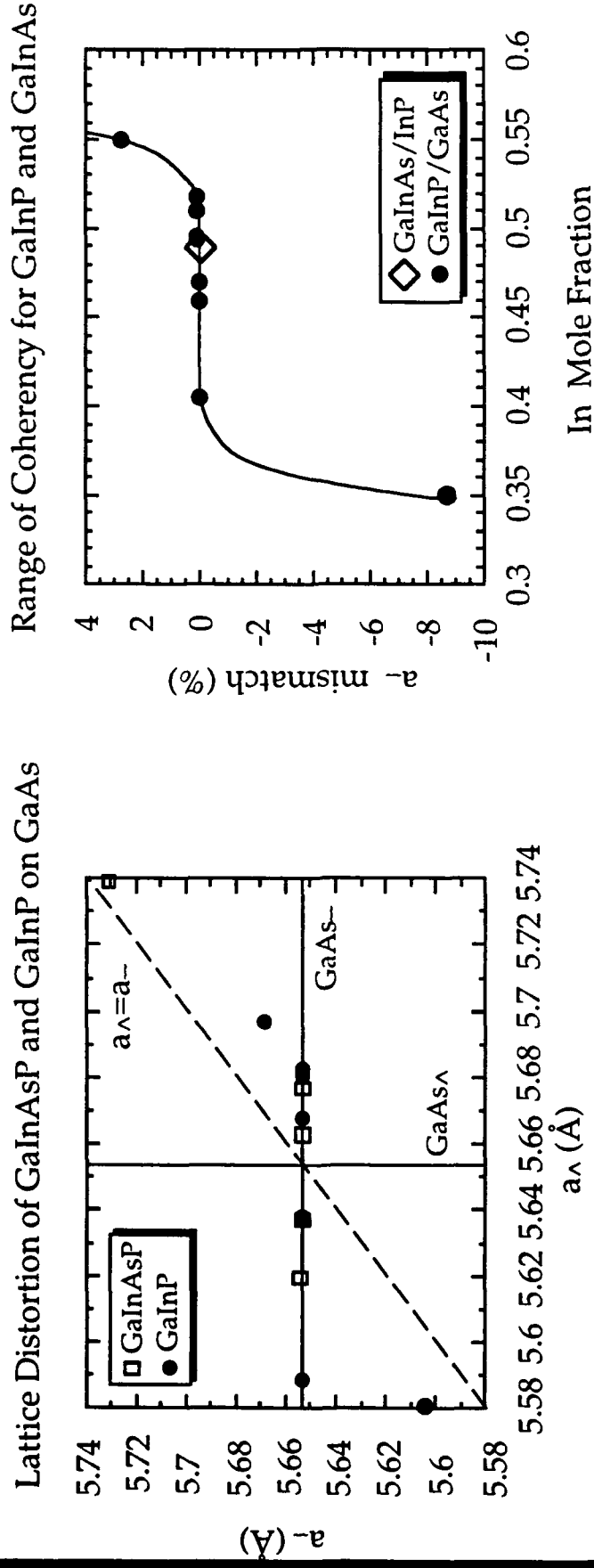
J. R. Shealy - Task 1

C. L. Tang - Task 2

C. R. Pollock - Task 3

J. P. Krusius - Task 4

Cornell JSEP (F49620-90-C0039) Task: J.R. Shealy OMVPE Growth of III-V Alloys for New High Speed Electron Devices

Coherency Range of GaInP/GaInAsP on GaAs and GaInAs on InP

Range of Coherency for GaInP and GaInAs

Lattice Distortion of GaInAsP and GaInP on GaAs

- Coherency range of GaInP over 10% In composition.

- Defect free surfaces observed with proper treatment of the reaction chamber.

- Cathodoluminescence reveals low dark line density over the entire coherency range.

- Tetragonal distortion range of GaInAsP is similar to GaInP.

Cornell JSEP (F49620-90-C0039) Task: C. L. Tang
Femtosecond Laser Studies of Ultrafast Processes in Compound Semiconductors

Objective: Development and applications of new broadly tunable femtosecond optical sources and techniques for studying ultrafast processes in semiconductors and quantum well structures.

Results: - Developed the first broadly tunable high repetition rate femtosecond optical source: the femtosecond optical parametric oscillator.
- Demonstrated the first intracavity doubling of the femtosecond optical parametric oscillator to cover the visible to near ir spectral range [see Fig. 1].
- Demonstrated the first femtosecond optical parametric oscillator using the new nonlinear optical crystal KTiOAsO$_4$ which can operate in the important 3 to 5 μm spectral range.
- Application of tunable femtosecond sources to study the relaxation dynamics of nonequilibrium carriers in GaAs and InGaAs [see Fig. 2].

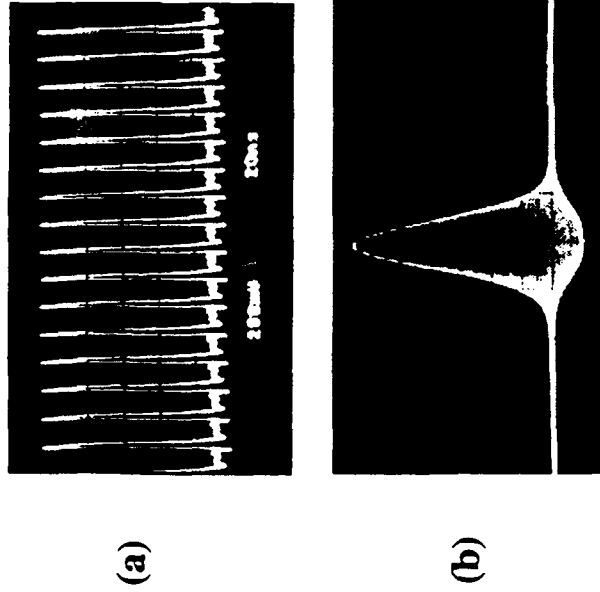## Spectra of Intracavity-doubled OPO

(a)

(b)

Fig. 1

- Demonstrated tuning range of the intracavity frequency-doubled OPO from 580 to 657 nm.
- Tuning is accomplished by rotating phase-matching angle of KTP, and optimizing output coupler and cavity length.
- Total power generated in second harmonic varies between ~80 and 240mW over range shown.
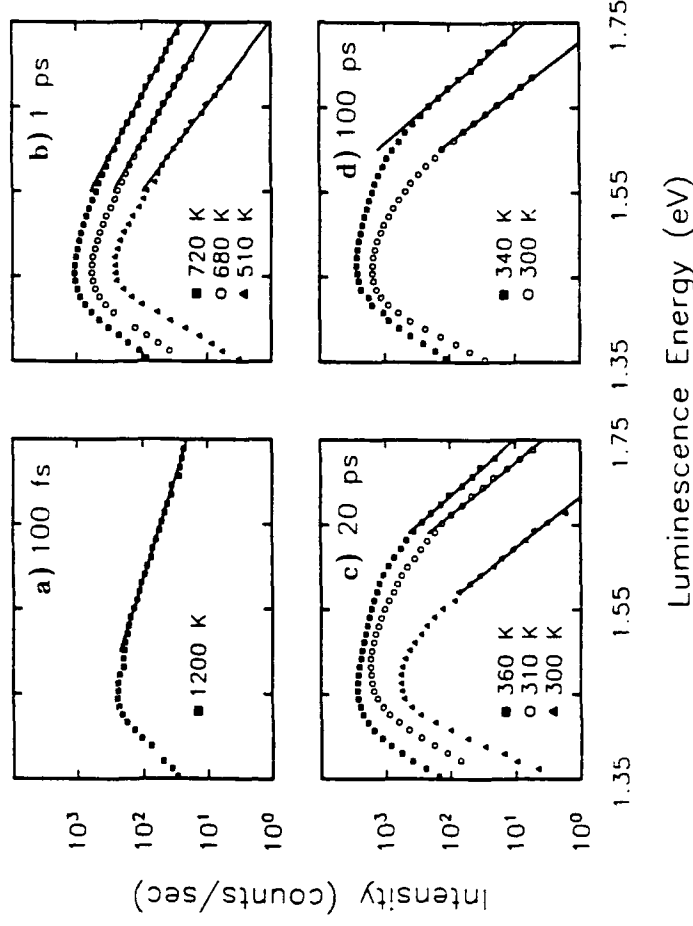
Figure 2 plots

a) 100 fs — ■ 1200 K

b) 1 ps — ■ 720 K, ○ 680 K, ▲ 510 K

c) 20 ps — ■ 360 K, ○ 310 K, ▲ 300 K

d) 100 ps — ■ 340 K, ○ 300 K

Intensity (counts/sec) vs Luminescence Energy (eV): 1.35, 1.55, 1.75

Fig. 2. Representative time-resolved luminescence spectra for the 4000-Å bulk GaAs sample at room temperature at each excitation power (squares, 1x10^{19} cm^{-3}; circles, 5x10^{18} cm^{-3}; triangles, 2x10^{18} cm^{-3}). The carrier temperature fits (straight lines) and values are shown for each carrier density at delay times of (a) 100 fs, (b) 1 ps, (c) 20 ps, and (d) 100 ps.

Cornell JSEP (F49620-90-C0039) Task: C.R. Pollock

Carrier Density Effects on Carrier Relaxation

Objective: Testing of the Monte Carlo modeling of Prof. Krusius (Task #4).

Results: Using pump-probe measurements of doped and undoped samples of $In_{0.53}Ga_{0.47}As$, we have confirmed the predicted effects of excess carrier concentration on the carrier relaxation time. The presence of excess carriers dramatically slows down the energy relaxation process.
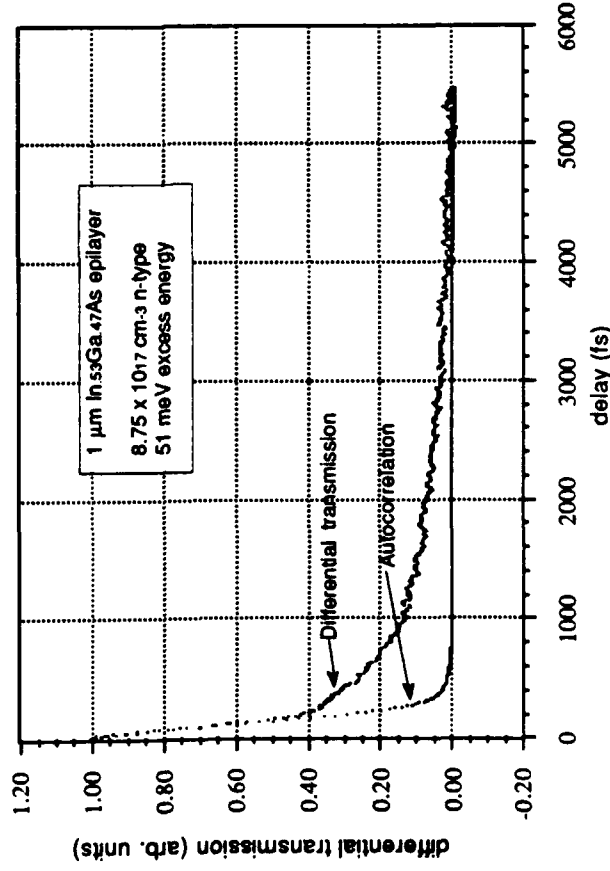
Fig. 1. Carrier relaxation in a sample with 8.75×10^{17} cm^{-3} n-type dopant. The photon energy is 51 meV greater than the bandgap. The autocor- relation trace is of the probe without a semiconductor sample.
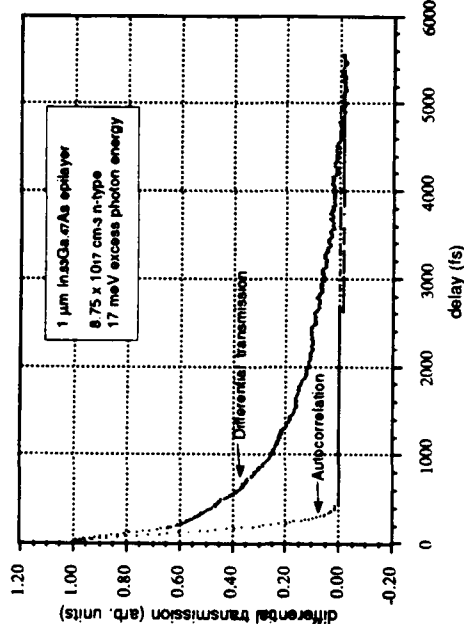
Fig. 2. Carrier relaxation in a sample with 8.75×10^{17} cm^{-3} n-type dopant. The photon energy is 17 meV greater than the bandgap.
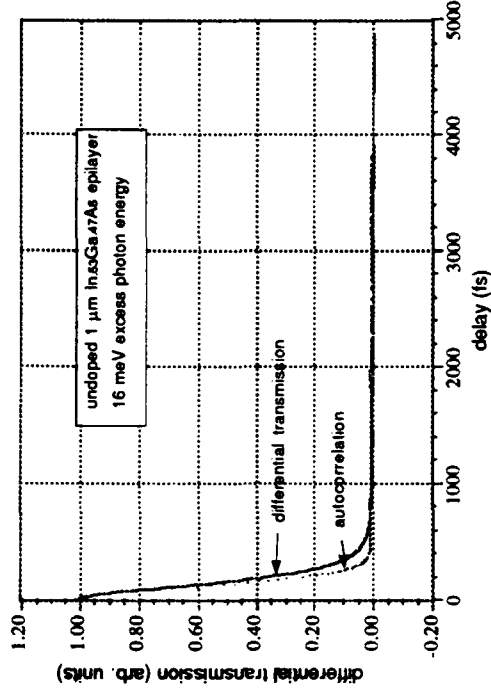
Fig. 3. Carrier relaxation in an undoped sample. The photon energy is 16 meV greater than the bandgap.

Cornell JSEP (F49620-90-C0039) Task: J.P. Krusius
Femtosecond Carrier Transport/Optical Interactions

Objective: Monte Carlo Modeling of Femtosecond Optical Probing

Results: Reproduced experimental data for a wide range of near band gap photon energies for InGaAs/InP

Provides foundation for quantitative understanding of carrier scattering and many body effects in compound semiconductors

Fig(s): Simulated pulse-probe vs. experimental dual-pulse correlation Band Gap: 0.750 eV for InGaAs